PERFORMANCE OF SPS LOW TRANSITION ENERGY OPTICS FOR LHC ION BEAMS

F. Antoniou, G. Arduini, H. Bartosik, T. Bohl, S. Cettour Cave, K. Cornelis, D. Manglunki, Y. Papaphilippou, CERN, Geneva, Switzerland

Abstract

An optics with low transition energy has been developed in the SPS for removing intensity limitations of the LHC proton beam and has become operational towards the second part of the 2012 LHC proton run. The impact of this optics in the performance of the LHC ion beam is studied here, especially with respect to collective effects, at the SPS injection energy, based both on modelling and beam measurements. In particular, the potential gain of the increased beam sizes provided by this optics, with respect to losses and emittance blow up due to space-charge and Intrabeam Scattering (IBS) is evaluated. The measured lifetime is compared with the one provided by the Touschek effect and its interplay with RF noise is studied.

INTRODUCTION

During the setting up of the ion beams at the SPS, a large spread on the beam parameters of the lead ion bunches at flat top was observed. Even though this is not a limitation for the performance of the LHC as lead ion collider, it would be interesting to overcome this bunch parameter spread, which is mainly dominated by processes at the flat bottom of the SPS [1]. A new optics, called Q20, with low transition energy, has been developed in the SPS for removing intensity limitations of the LHC proton beam. As this optics improved the performance of the SPS proton beams [2], it was proposed to be used as an alternative for the ion beams too for reducing scattering effects and space charge, due to its larger beam sizes. In this paper, a comparison between the nominal (Q26) and Q20 optics with respect to collective effects like space charge, Intrabeam Scattering (IBS) and Touschek scattering is presented. The interplay between the collective effects and the RF noise is also discussed.

SCATTERING EFFECTS IN THE ION BEAMS AT THE SPS

One of the advantages of the Q20 optics with respect to scattering effects is the larger dispersion (peak values by almost a factor of 2 higher and larger beta functions), so that the average beam sizes are increased by almost 50% in the horizontal and 10% in the vertical plane. This has an impact on the incoherent space charge tune-shift, given by the Laslett formula, which is reduced by 15%, from $\Delta Q_y = -0.15$ for the Q26 to $\Delta Q_y = -0.13$ for the Q20 optics, assuming the beam parameters presented in Table 1, which correspond to the SPS ion beam as delivered to the LHC during the 2011 run.

Table 1: Main parameters of the ion beam at the SPS

Parameters	Value
Bunch population [10^8]	2.4
Pb^{82+} classical radius [m]	5×10^{-17}
Relativistic γ/β	7.31/0.99
rms bunch length [m]	0.3
rms energy spread	3.25×10^{-4}
Transverse norm. emittances [mm-mrad]	0.8×10^{-4}

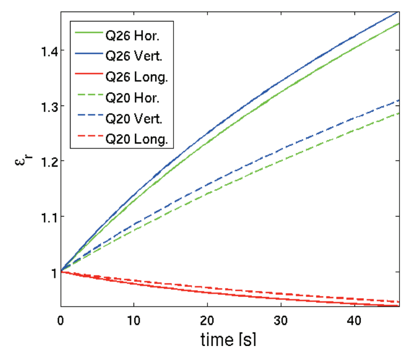

Figure 1: IBS relative emittance evolution in the hor. (green), vert. (blue) and long. (red) planes, for the Q20 (dashed lines) and Q26 (solid lines) optics, for the same initial conditions.

The increase of the beam sizes has an impact also on the expected emittance dilution with time, due to intrabeam scattering (IBS). Figure 1 shows a comparison of the IBS effect for the nominal Q26 (solid lines) and the Q20 (dashed lines) optics in the horizontal (green), vertical (blue) and longitudinal (red) planes, for the same initial conditions and current. The Piwinski formalism [4] was used for the calculation of the IBS growth rates and the emittances' evolution with time for a cycle duration of 40 sec. In both cases, transverse emittance growth and longitudinal emittance damping with time is predicted. The effect in the transverse plane is $\sim 15\%$ larger in the Q26 than the Q20 optics, while in the longitudinal plane the effect is almost the same.

In the large scattering angle limit of the Coulomb scattering, the Touschek effect leads to beam losses due to large exchange of momentum between the colliding particles. The non-relativistic round beam approach of the Touschek lifetime can be found in [3]. Assuming a general quadratic

ISBN 978-3-95450-122-9

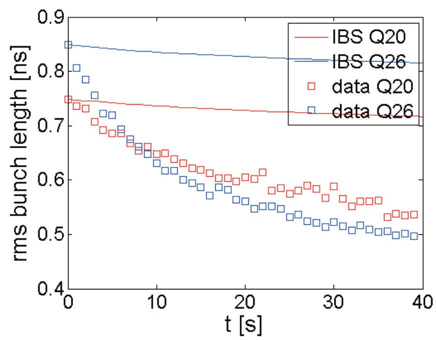

Figure 2: Measured (squares) and IBS predicted (solid lines) bunch length evolution with time for the Q26 (blue) and the Q20 (red) optics.

form for the current decay with time:

$$\frac{dI}{dt} = -\frac{I}{b} - \frac{I^2}{a}, \tag{1}$$

the time depended current expression is given by:

$$I(t) = \frac{\alpha I_0 e^{-t/b}}{b I_0 (1 - e^{-t/b}) + \alpha}. \tag{2}$$

Comparing Eq. (1) with the Touschek lifetime expression, the parameter α, called the Touschek parameter, can be calculated analytically, and has a complicated dependence on the beam energy spread, bunch length and transverse emittances, the optics and the minimum acceptance of the machine at each location. For the case of the SPS, we consider that the minimum acceptance is the RF momentum acceptance. The parameter b corresponds to the lifetime factor due to other effects, such as RF noise.

Considering the same beam parameters as defined in Table 1, the analytical Touschek parameter for the Q26 optics is $\alpha = 0.1546$ mA·sec, while for the Q20 optics $\alpha = 0.3038$ mA·sec, which indicates that the Touschek contribution to the lifetime expression is expected to be a factor of 2 larger for the Q26 optics.

MACHINE STUDIES

During the setting up of the ion beams at the SPS for the 2011 LHC run (11/2011), a spread on the beam parameters of the lead ion bunches at flat top was observed. In this respect, it was crucial to investigate the contribution of IBS and Touschek to this spread.

Figure 2 shows the measured bunch length evolution with time for the Q26 (blue squares) and Q20 (red squares) optics. Starting from the measured value at injection, the bunch length evolution with time due to IBS was computed, where for each point the bunch current was updated according to the measured one. The results are shown in solid lines in blue for the Q26 and in red for the Q20 optics. Even though IBS predicts bunch shortening, the resulting effect is much smaller than the observed one.

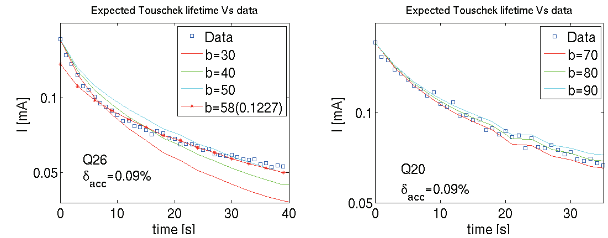

Figure 3: Measured (blue squares) and expected Touschek (solid lines) current decay with time for the Q26 (left) and Q20 (right) optics.

In order to estimate the expected current decay with time due to the Touschek effect, the Touschek parameter is calculated for each measured bunch length, considering the horizontal and vertical emittances unchanged, as at that point no transverse emittance increase with time was observed in the machine. As the calculations are very sensitive to the momentum acceptance, which is not a well known parameter for the SPS, the Touschek estimates are computed for different acceptance values, assuming, as first approximation, that it is constant around the ring. The expected current decay with time can then be calculated from Eq. (2), while b is used as a free parameter. Figure 3 shows one example of the measured current decay with time (blue squares) while the solid lines show the estimated decay with time based on the above calculations, for different values of the b factor. For the Q26 optics (left), there is no b parameter for which a "Touschek like" behaviour applies to all data. However, considering that fast losses at the beginning of the injection process can be due to other effects (e.g. space charge), which are not linear with time and cannot be included in the b parameter, and by ignoring the first few measured points, the rest of the current data seem to follow a "Touschek like" behaviour. On the other hand, the data from the Q20 optics (right), seem to follow a "Touschek like" behaviour from the beginning.

As the analysis is still in a preliminary stage, what can be stated for now is that a nonlinear, "quadratic", term is needed to describe the current decay of the ion beams at the SPS, which is not clear if it is due to a scattering effect or the interpaly between scattering and other effects like RF noise and space charge, which is not known what is their contribution to lifetime.

After an upgrade and optimization of the low-level RF system in 2012 which minimised the contribution of the RF noise to the lifetime [5], a comparison of the beam lifetime for the Q26 and Q20 optics showed a better lifetime for the Q20 optics, as expected from the theoretical calculations. Figure 4 shows this comparison with the lifetime for the Q20 shown in purple and for the Q26 in blue.

In January 2013, a new set of measurements was performed in order to evaluate the impact of different RF voltage (V_{rf}) and different synchro loop gain (SLG) settings on the evolution of the lifetime along the flat bottom. The measurements were performed for the fixed-target (FT) ion

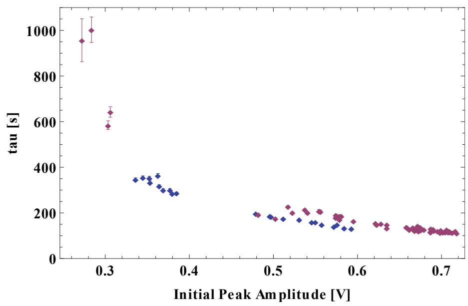

Figure 4: Lifetime comparison between the Q20 (purple) and the Q26 (blue) optics, after the optimization of the low-level RF system.

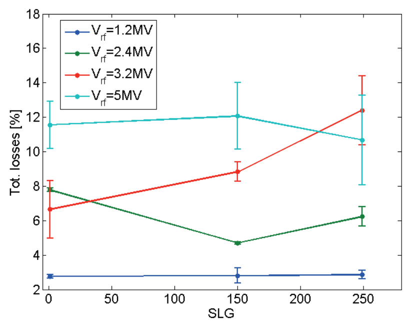

Figure 5: Dependence of the total losses along the first injection period on the RF voltage and the synchro loop gain (SLG).

beam. As this beam is set up for a slow extraction scheme, the fractional part of the tune is set above the half integer and below the third order resonance lines, and is different than the one chosen for the LHC ion optics. Figure 5 shows the dependence of the total losses for the first injection period on the RF voltage and the SLG. The total losses are minimized for the lower RF voltage (1.2 MV) and for this setting the dependence on the SLG is minimal. On the other hand, operational experience showed that the optimal RF voltage for the operation of the SPS is 3.2 MV. For this voltage, losses are minimized for the smallest SLG (SLG=1).

Figure 6 shows the beam lifetime along the flat bottom for the optimal conditions (V_{rf}=3.2 MV, SLG=1). The different curves correspond to different measurements for the same settings. In this case, the lifetime follows a different behavior than the "Touschek like" one observed in the 2011 data. Transverse emittance measurements were also performed, where both horizontal and vertical emittances were measured to be constant along the flat bottom, with $\epsilon_x = 2\mu$m-rad and $\epsilon_y = 1.5\mu$m-rad, normalized. Those values are much larger than the expected ($\epsilon_{x,y} = 0.8\mu$m-rad) and the beam has a non-Gaussian beam profile. This could be an indication of emittance blow up caused by resonance crossing due to the large space charge tune-shift, as those measurements were performed for a different beam

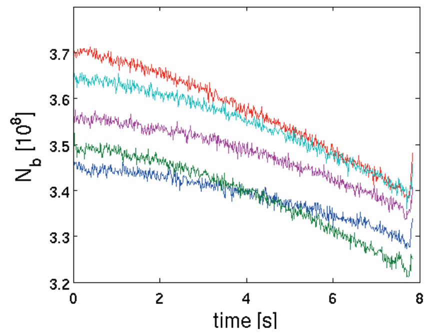

Figure 6: Lifetime along the flat bottom with the fixed-target beam.

(FT) with a working point close to the half integer resonance. The same effect was seen during the 2011 run when the working point of the LHC ion beam was put close to the integer resonance. This can explain a fast emittance blow up, which then puts the beam out of the scattering regime, leading to a constant emittance with time, and the transverse losses are dominated to the scraping of the tails by machine aperture restrictions.

SUMMARY AND OUTLOOK

During the 2011 setting up of the ion beams at the SPS, a large spread on the beam parameters of the lead ion bunches at flat top was observed. This can be attributed to an interplay between RF noise and collective effects, like IBS, Touschek and space charge. Comparison, based on theoretical calculations for same beam conditions, between the old (Q26) and the new (Q20) optics showed that both scattering effects and space charge are expected to be reduced with the new optics due to larger beam sizes. After an upgrade of the low-level RF system of the SPS, which led to the minimisation of the RF noise conribution to the beam lifetime, a lifetime comparison between the two optics showed a better performance of the Q20 optics. Transverse emittance and beam lifetime measurements under different beam conditions gave hints for the existence of both space charge and scattering effects. In order to study those effects and the interplay between them, dedicated measurements at different working points and different currents are required, for finding optimal conditions that overcome the large spread of the beam parameters while having good transmission to the LHC.

REFERENCES

[1] T. Bohl, Note 2011-72, CERN, Geneva, November 2011.

[2] H. Bartosik et al, proc. of IPAC12, New Orleans, 2012, WEPPR072.

[3] A. Piwinski, arXiv:physics/9903034.

[4] A. Piwinski, Proc. 9th International Conference of High Energy Accelerators, Standford, CA, p.405, 1974.

[5] T. Bohl, Note-2013-02, https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=242146

ISBN 978-3-95450-122-9